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Final Technical Report  
For:

The Air Force Office of Scientific Research  
Electronic and Material Sciences Directorate

Reconfigurable Opto/Electronic Multiprocessor Interconnection Structures

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## Project Summary

**This research extended our previous research in communications, control, and arbitration for optical fiber technology to multiprocessor multi-stage interconnection structures. In particular, have developed a new architecture and a new class of control algorithms which are appropriate for many space, wavelength and time switched reconfigurable optical interconnection structures. The algorithms use the locality in the message traffic of multiprocessor systems to reduce the control overhead associated with optimal reconfiguration.**

# **1 Project Objectives**

Our research has been an investigation of the design issues for a highly scalable multiprocessor interconnection network using optical technology to overcome the wiring complexity and cost of conventional systems. The issues to addressed were scalability and throughput. To overcome the problem of scalability caused by fanout limitations, the system must be based on a reconfigurable interconnect. To overcome the throughput problem which comes from the bottleneck of message routing and control we must amortize the control overhead over several messages. We do this using the locality in the message traffic. The technique is called state sequence routing. It uses no explicit address headers, rather the network is stepped though a repeated sequence of routing states. This is similar to multiplexing, but only uses the states required to meet the current needs of the message traffic. The control sequence evolves over time to the changing traffic needs. Control bandwidth requirements are reduced to the speed of changes in the message traffic rather than the speed of the messages themselves. The relevance (and dual use) of this work comes from the need to provide multiprocessor interconnection structures for the next generation of parallel supercomputers which will be required for both military and commercial applications.

## **2 Major Project Contributions**

### **2.1 Partitioned Optical Passive Star Architecture**

This portion of the project resulted in a scalable electro-optical interconnection network architecture which is suitable for tightly coupled multiprocessors. The architecture is called a Partitioned Optical Passive Star (POPS). It is a type of multiple passive star topology in which only constant and symmetric coupler fanouts are used and in which exactly one coupler is traversed on any path through the network. Control is based on the state sequence routing paradigm which multiplexes the network between a small set of control states and defines a control operation to be a transformation of those states.

These networks have highly scalable characteristics for optical power budget, resource count, and message latency. Optical power is uniformly distributed and the size of the system is not hard limited by the power budget. Resource complexity grows with asymptotic complexity  $O(n)$  for the couplers,  $O(n\sqrt{n})$  for transceivers, and  $O(\sqrt{n} \log(n))$  for control. In this work, we developed a static analysis and a simulation of dynamic performance which demonstrates the ability of a POPS design to support 1024 nodes using current device and coupler technology. Detailed presentations of these results were made in publications [3][7][8][10] and [14].

### **2.2 Distributed State Sequence Routing Control**

Hybrid optoelectronic computing structures are required to provide the information processing capabilities for the next generation of computing and communications systems. Reconfigurable optoelectronic interconnection networks are networks constructed of optical waveguides in which messages are switched or routed by means of optoelectronic devices. For these networks, the dichotomy between the bandwidth of the optical channels which carry messages and the performance of the electronic controllers and decoders which determine the routing and destination of those messages is a significant bottleneck. We have introduced a new class of routing algorithms for reconfigurable networks designed to bridge this gap in optical versus electronic performance. The algorithms are based on a new control paradigm which exploits the locality in multiprocessor communication streams to reduce the control latency inherent in reconfigurable interconnection structures. In addition, we have shown that this problem maps directly to the problem of page replacement in a virtual memory hierarchy. Thus, our solution is well suited to networks for multiprocessor applications. The results from this portion of the project are reported in [5][9][11][13][15][17][18][20][21] and [23].

### **2.3 Predictive Control of Opto-Electronic Reconfigurable Interconnection Networks Using Machine Learning**

As an extension to our work in State Sequence Control, a prediction unit (PU) was trained on-line to learn and predict repetitive memory access patterns for three applications, 2-D relaxation algorithm, matrix multiply and Fast Fourier Transform. The predictions were used by a state sequence routing control algorithm to reduce control latency by providing needed paths before they

were requested. Hiding the control latency seen by each access improves multiprocessor performance significantly. The new technique hides control latency by employing a time-delay neural network (TDNN) as a prediction technique that learns the current processor-memory access patterns and predicts the need to reconfigure the IN. Training and prediction of the TDNN is performed on-line. The TDNN is able to learn repetitive patterns and predict the need to reconfigure the IN thus, effectively hiding control latency of processor-memory accesses. These results are reported in [1][4][6].

### 3 Project Publications

- [1] "Performance of On-Line Learning Methods in Predicting Multiprocessor Memory Access Patterns"; M. F. Sakr, S. P. Levitan, D. M. Chiarulli, C. L. Giles, B. G. Horne; *Neural Computation* (submitted).
- [2] "An Optoelectronic Cache Memory System Architecture"; D. M. Chiarulli, S. P. Levitan; *Applied Optics* 34(14):2449-2456, 10 May 1996.
- [3] "Partitioned Optical Passive Star (POPS) Multiprocessor Interconnection Networks with Distributed control". D. Chiarulli, S. Levitan, R. Melhem, J. Teza and G. Gravenstreter, *IEEE Journal of Lightwave Technology*, 14(7):1601-1612, July 1996.
- [4] "On-Line Prediction of Multiprocessor Memory Access Patterns"; Majd F. Sakr, C. Lee Giles, Steven P. Levitan, Bill G. Horne, Marco Maggini, Donald M. Chiarulli; **International Conference on Neural Networks**; Washington, D. C.; June 3-6, 1996.
- [5] "Reconfiguration and Routing in Interconnection Networks using Time Division Multiplexing"; R. Melhem, C. Qiao, D. Chiarulli and S. Levitan; (in) *Parallel Computing Vol.*; Albert Zomaya Ed.; Jesshope and Sahni Series Eds. Chapman & Hall (1995).
- [6] "Predictive Control of Opto-Electronic Reconfigurable Interconnection Networks Using Neural Networks"; Majd F. Sakr, Steven P. Levitan, C. Lee Giles, Bill G. Horne, Marco Maggini, Donald M. Chiarulli; **Second International Workshop on Massively Parallel Processing Using Optical Interconnections**; pp. 326-335; San Antonio, TX October, 1995.
- [7] "Embedding Rings and Meshes in Partitioned Optical Stars Networks"; G. Gravenstreter and R. Melhem; **Second International Workshop on Massively Parallel Processing Using Optical Interconnections**; San Antonio, TX October, 1995.
- [8] "The Partitioned Optical Passive Stars (POPS) Topology"; G. Gravenstreter, R. Melhem, D. Chiarulli, S. Levitan and J. Teza; **Proc. of the 9th. International Parallel Processing Symposium**; pp. 4-10; Santa Barbara, CA, April 25-28, 1995.
- [9] "Reconfiguration with Time Division Multiplexed MINs for Multiprocessor Communications"; C. Qiao, R. Melhem; *IEEE Trans. on Parallel and Distributed Systems Vol. 5*, No. 4; pp. 337-352; April 1995.
- [10] "Multiprocessor Architectures using Partitioned Optical Passive Star Interconnection Networks"; J. P. Teza, D. M. Chiarulli, S. P. Levitan, R. G. Melhem, G. Gravenstreter; **OC'95, Optical Society of America Optical Computing Topical Meeting**; pp. OMB-3, Salt Lake City, UT, March 12-17, 1995.
- [11] "Reducing Communication Latency with Path Multiplexing in Optically Interconnected Multiprocessor Systems"; C. Qiao and R. Melhem; **Proc. of the International Symposium on High Performance Computer Architecture**; pp. 34-43; Raleigh, NC; January 22-25, 1995.

- [12] "Optoelectronic Buses for High Performance Computing"; D.M. Chiarulli, S.P. Levitan, R.G. Melhem, M. M. Bidnurkar, R. M. Dittmore, G. Gravenstreter, Z. Guo, C. Qiao, J. Teza; *IEEE Proceedings*, Vol. 82, No. 11, pp. 1701-1710; November, 1994.
- [13] "A Time Domain Approach for Avoiding Crosstalk in Optical Blocking Multistage Interconnection Networks"; C. Qiao, R.G. Melhem, D.M. Chiarulli, S.P. Levitan; *IEEE Journal on Lightwave Technology* Vol. 12, No. 10, pp. 1854-1862; October, 1994.
- [14] "The Partitioned Optical Passive Stars POPS Topology"; G. Gravenstreter, R. Melhem, D. Chiarulli, and S. Levitan; Department of Computer Science, University of Pittsburgh, TR-94-43, September 1994.
- [15] "Dynamic Reconfiguration of Optically Interconnected Networks with Time Division Multiplexing"; Chunming Qiao, R.G. Melhem, D.M. Chiarulli, S.P. Levitan; *Journal of Parallel and Distributed Computing*, Vol. 22, No. 2, pp. 268-278; August, 1994.
- [16] "Multiprocessor Interconnection Networks Using Partitioned Optical Passive Star (POPS) Topologies and Distributed Control"; Donald M. Chiarulli, Steven P. Levitan, Rami G. Melhem, James P. Teza, Greg Gravenstreter; **First International Workshop on Massively Parallel Processing Using Optical Interconnections**; pp. 70-80; Cancun, Mexico; April 26-27, 1994.
- [17] "Locality Based Control Algorithms for Reconfigurable Optical Networks"; D.M. Chiarulli, S.P. Levitan, R.G. Melhem, C. Qiao; *Applied Optics*, Vol. 33, No. 8; pp. 1528-1537 March 10, 1994.
- [18] "Simulation of Efficient Routing in TDM Optically Interconnected Multiprocessor System"; C. Qiao, R. Melhem, D. Chiarulli and S. Levitan; **Proceedings of the 1993 25th Annual Summer Computer Simulation Conference (SCSC'93)**; pp. 320-325; Boston, MA; July 19-21, 1993.
- [19] "Time-Division Optical Communications in Multiprocessor Arrays"; C. Qiao and R. Melhem; *IEEE Trans. on Computers* vol 42, no 5; pp. 577-590; 1993.
- [20] "Bandwidth as a Virtual Resource in Multiprocessor Interconnection Structures"; D. M. Chiarulli, S. P. Levitan, R. Melhem, C. Qiao; **Optical Computing Technical Digest**, Optical Society of America, Vol.7, Pages 299-302; Palm Springs, CA, March 15-19, 1993.
- [21] "A Time domain approach for avoiding crosstalk in MINs"; C. Qiao, R. Melhem, D. M. Chiarulli, S. P. Levitan; **Optical Computing Technical Digest**, Optical Society of America; (poster) Palm Springs, CA, March 15-19, 1993.
- [22] "Model of Lossless Bus Structure Using Erbium Fiber Amplifiers Pumped near 820nm"; M. M. Bidnurkar, S. P. Levitan, R. Melhem, D. M. Chiarulli; **Optical Computing Technical Digest**, Optical Society of America; (poster); pp. 192-5; Palm Springs, CA, March 15-19, 1993.
- [23] "Efficient Routing in TDM Optically Interconnected Multiprocessor Systems"; C. Qiao, R. Melhem, D. M. Chiarulli, S. P. Levitan; **SPIE Symposium on OE/Aerospace Sensing'92, Conf. on Advances in Optical Information Processing V**; Orlando, Fl.; Proc. SPIE Vol.1704:428-39; April 21-24, 1992.